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SEARCH FOR NEUTRINO-PRODUCED MAGNETIC MONOPOLES IN A BUBBLE CHAMBER EXPOSURE

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J. Schwinger has suggested that magnetically charged particles could be produced *via* a magnetically charged intermediate boson process similar to the mechanism sometimes envisioned for double muon production by neutrinos. A search for magnetic monopole production by neutrinos has been made by reexamining the CERN heavy liquid bubble chamber pictures obtained during the neutrino exposures of 1963 and 1967. Five different searches were made for events which contained a free monopole with and without target nucleus excitation, and for bound monopoles which deexcited by photon emission. No events were found. Neutrino monopole production cross-section limits are given.

1. Introduction

The natural time reversal violation present in magnetic monopole systems has reawakened interest in these systems since the discovery of the violation of charge conjugation in K^0 decays. Carrigan [1], Schwinger [2], and Barut [3], have suggested that the underlying constituents of matter may be mixed systems of magnetic monopoles and electric charges. Schwinger uses magnetic quarks, called dyons, to construct an SU(3) system without the requirement of a hypercharge label for the quarks. There are difficulties, however, with large time reversal violations and the electric dipole moment of the neutron. These problems can be alleviated by incorporating a magnetic boson charge exchange mechanism into the model. Schwinger has suggested that this boson may be coupled in turn to the normal weak interactions.

Previously we reevaluated the existing cosmic ray monopole searches to obtain an upper limit for monopole production by neutrinos [4]. We noted that the cross-section limits obtained for direct production of monopoles by neutrinos produced by cosmic rays would be comparable to limits set in neutrino bubble chamber exposures for the monopole mass range accessible with accelerator beams. Since interactions in a bubble chamber are collected under more controlled and well-under-

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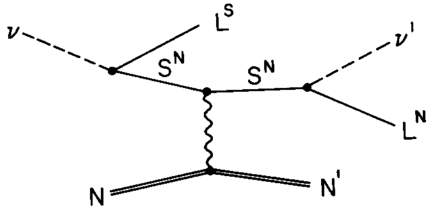

Fig. 1. Intermediate-magnetic-boson mechanism for the production of a magnetic lepton pair.

stood conditions than in cosmic-ray experiments, we have rescanned part of the existing neutrino bubble chamber film to look for monopole events and establish more reliable limits. In addition the bubble chamber offers the possibility of detecting gamma rays from the de-excitation of bound monopole systems. Ruderman and Zwanziger [5] and Newmeyer and Trefil [6] have argued that the huge attractive strength of such a pole system makes it extremely difficult for two poles to become unbound. Instead, the deexcitation radiation from the two poles will give rise to a soft photon shower. A heavy liquid bubble chamber is an ideal detector to observe these showers.

Neutrino production of pairs of poles can occur via a diagram similar to those suggested for the "normal" intermediate vector boson as shown in fig. 1. In the process the normal intermediate boson is replaced by S, the Schwinger magnetic boson. The final state products (L^N, L^S) can be either magnetic leptons or a combination of a magnetic lepton and a magnetic hadron of the sort suggested by Han and Biederharn [7]. If the production is incoherent there may be excitation of the target nucleus, i.e., the production of additional elementary particles or spallation of the nucleus. Hence a candidate in the bubble chamber may contain both magnetic and conventional tracks.

2. Technique

2.1. Event description in a bubble chamber

If free magnetic poles were produced in interactions in the bubble chamber, the north and south poles would rapidly slow down because of their very high ionization loss, 400 MeV/cm for a single Dirac magnetic charge. Estimates indicate that the resulting range in a heavy freon (CF_3Br) filling of the bubble chamber would be less than a bubble diameter for a monopole of a single Dirac charge. After the monopoles have stopped they would move along the field lines of the chamber with velocities characteristic of a diffusion process, typically 10^6 cm/sec. For normal Dirac charges the transit time across the bubble chamber would be several hundred microseconds. The transit time would lengthen if the pole were bound to other objects, had an intrinsically large mass, or had a small magnetic charge. For the CERN

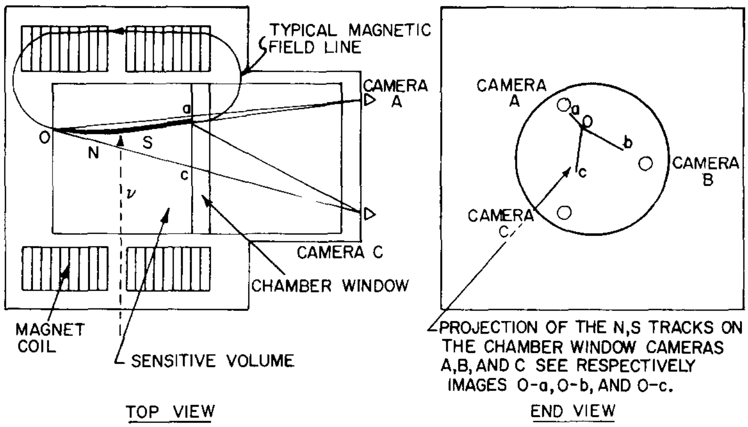

Fig. 2. Illustration of a monopole event in the CERN heavy liquid bubble chamber. The top view shows the oppositely charged monopoles move along field lines. The end view shows the two tracks appearing as a straight line pointing toward the appropriate camera optical axis.

neutrino exposure the sensitive time of the bubble chamber was on the order of several milliseconds. Under extreme conditions it is possible that the diffusion time might have been longer than the sensitive time of the chamber resulting in monopole tracks appearing as stopped tracks.

One can question whether magnetic poles diffusing across the bubble chamber would have produced visible tracks. The diffusing monopoles would be moving slowly and would lose energy by elastic collision processes of one sort or another. However, the energy loss would still be extremely high, ~400 MeV/cm times the magnetic charge in units of the Dirac magnetic charge. This energy would ultimately have to appear as a thermal spike in the liquid. Although the theory of bubble chamber track formation is not completely understood, indications are that the thermal spike arising from the energy loss rather than the ionization itself, is the ultimate source of the bubbles [8]. Thus it seems plausible to assume that the tremendous thermal spike from a monopole passing across the chamber would give rise to a perceptible track. A monopole track may appear quite dense since the energy loss would be many times that of a normal ionizing particle.

We have used the heavy liquid bubble chamber film from the CERN neutrino exposures in 1963 and 1967 [9,10] to search for tracks arising from monopole production. In the case of the CERN 1.1 m heavy liquid bubble chamber the camera optical axes are horizontal and parallel to the field lines at the center of the chamber (see fig. 2). This is an optical configuration which allows rapid and certain rejection of rigid cosmic ray background tracks as candidates. The projection of the optic axis for a particular camera can be thought of as a point on the photographs from that camera (see also fig. 3). The projection of the magnetic field lines on the photo-

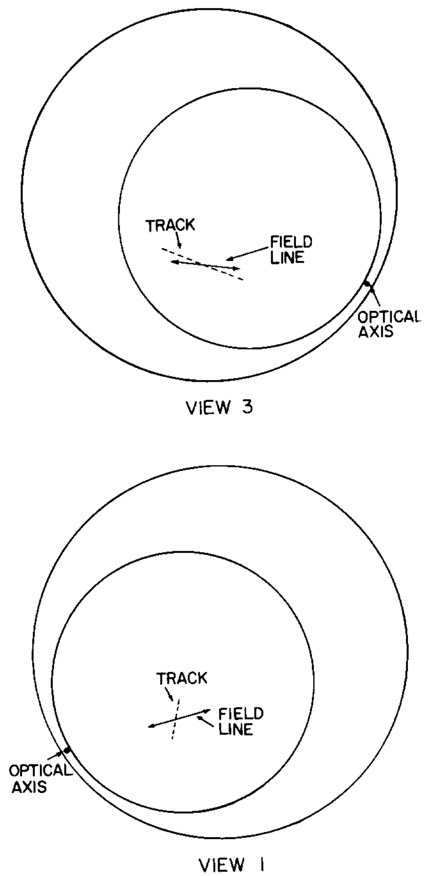

Fig. 3. Two views of a poor candidate for a monopole pair track. The inner circle is the far end of the chamber and the outer circle is the near end. The dotted lines are facsimilies of the track. The solid lines show the projection of a field line lying near the track. In view "3" the candidate roughly follows the field line and is approximately the same length. However, in view "1" the track is almost orthogonal to the field line.

graph can be visualized as straight lines diverging from the optical axis point. Therefore, for a given camera view a particle moving along a field line will always produce an image on the film plane which points back to the optical axis point. Furthermore, the combined tracks from a north-south pair each moving along a field line and passing out of the chamber will have a well determined image length which increases as the distance of the track from the optical axis increases. The magnetic field lines were not completely symmetric about the mid-plane of the chamber. The field lines at the camera end bent slightly so that the monopole trajectories projected on the film plane would not be exactly straight lines. This bending has been determined and was potentially a convenient tool for resolving ambiguities between *monopoles* tracks and rigid horizontal cosmic-ray tracks which passed through the chamber. Estimates indicate that one to ten such muon tracks should have occurred in the exposure that we examined and have been able to pass our extremely loose scan criteria. Here the lack of curvature of the tracks at the camera end could help to identify these tracks as cosmic rays tracks.

It is also possible to search for bound magnetic poles in a heavy liquid bubble chamber. Following the Ruderman-Zwanziger hypothesis, we would expect a well-developed photon shower within a bubble chamber filled with a short radiation length liquid. We examined film from both the 1963 heavy freon exposure (radiation length 11 cm) and the 1967 propane exposure (radiation length 109 cm). The Ruderman-Zwanziger process should be easily observed since the probability of converting a single photon is greater than 95% in the heavy freon exposure and about 40% in the propane exposure

2.2. *Scan criteria*

Five different analysis of four different scans of the film were used to investigate:

(i) Free monopole production without target excitation and $t_D < t_S$, where t_D is the diffusion time of the monopoles and t_S is the sensitive time of the bubble chamber.

(ii) Free monopole production with target excitation and $t_D < t_S$.

(iii) Free monopole production with target excitation and $t_D > t_S$.

(iv) Free monopole production without target excitation and $t_D > t_S$.

(v) Bound monopole excitation with and without target excitation.

We will now discuss each of these searches in more detail.

In the first approach a direct scan was made of one-tenth of the film from the 1967 propane exposure. Very loose criteria were established to select tracks traveling approximately along magnetic field lines, i.e., those which roughly pointed back to the optic axis. No ionization criteria, straightness requirements, or lack of kinks was placed on the requirements for an acceptable event. The scanners scanned one view of the film using a template which helped to identify tracks passing through the chamber approximately along field lines. If a track roughly pointed back to the optic axis in the first view, the scanner examined the second view and checked to see if the track pointed back to the optic axis there. The scan on one view alone netted about ten possible events. Physicists were able to discard all of these events at the scan table without resorting to geometrical reconstruction of the tracks because they failed to point to the optic axes in all three views Part of the film scanned by scanners was also scanned by physicists. Rolls containing events were occasionally rescanned to see if different scanners could identify events with the same character. Fig. 3 shows two views of a monopole candidate which passed our loose scan criteria for view "3." The solid lines show the approximate geometry of a field line passing through the chamber near the track. Note that in view "1" the particle track is distinctly different than the field line projection. In addition, the particle in the photograph was only lightly ionizing.

The second and third searches were made using the following technique. All the neutrino candidates with vertices in the chamber had previously been photographed and cataloged for the original neutrino experiments. We considered the possibility that monopole events could have been produced along with additional elementary particles or nuclear spallation at the hadron vertex so the events would have been cataloged as conventional neutrino events. Therefore, all of the previously identified neutrino candidates were rescanned for tracks traveling along the magnetic field lines. Again very loose criteria were used to allow for tracks stopping in the liquid, excessive diffusion, and so on. No events were found which satisfied these criteria.

The fourth technique involved an examination of the proton recoil candidates in the 1967 experiment. In the neutrino experiment all of the proton recoil candidates, i.e., all single tracks which were contained completely within the chamber, had previously been recorded by tracing the tracks on graph paper, preserving their directions relative to the optic axes and their lengths. These tracks could be interpreted as monopoles with very long diffusion times such that their transit times across the chamber were greater than the sensitive time of the chamber. All of these tracks were tested to determine if any of them were directed along the magnetic field lines. No candidates were found.

The fifth scan consisted of a search for unusual gamma showers in the neutrino exposures. In prior scans all gamma-ray showers with more than 20 cm of track on projection had been recorded. These events were rescanned to see if any resembled showers following the Ruderman-Zwanziger hypothesis, that is, showers with a large number of gamma rays with no other explanation. If an event had been found which appeared to satisfy the criteria, identification as a monopole event would have been quite difficult because the spectrum on the Zwanziger-Ruderman hypothesis might easily have been faked by a number of other processes. However, no events of this sort were identified in the original scan. All candidates were consistent with $\leqslant 3\pi^0$ production. We also rescanned one-tenth of the propane film for unusual gamma rays without the requirement of more than 20 centimeter of tracks. No events were found.

In summary none of the five different scans produced any events which even faintly resembled free monopole production or excitation of a bound monopole system.

3. Analysis [11]

The number of monopole pairs produced by the neutrino flux per proton, $\mathrm{d}N/\mathrm{d}E_\nu$, in the chamber is given by

$$N_m = \frac{N_A}{A} \rho V N_p \int_{E_T}^{E_M} \sigma_c(E_\nu) \frac{dN}{dE_\nu} \, dE_\nu ,$$

where N_A is Avogadro's number, ρ is the operating density of the chamber material, V is the fiducial volume of the chamber, A is the effective mass number for the chamber material, E_T is the threshold energy, N_p is the number of protons on the neutrino production target, and E_M is the maximum neutrino energy. $\sigma_c(E_\nu)$ is the cross section per nucleus.

In the 1967 CERN propane bubble chamber neutrino exposure the volume of the chamber was 0.95 m [3]. This has been taken as the fiducial volume for this search. Effectively the chamber was a target with a diameter of 1.1 m and depth of 1 m. The operating density was $\rho = 0.44$ g/cm^3 and the effective A value was 14.7. The neutrino energy spectrum is shown in fig. 4. The neutrino flux through the chamber for the entire proton exposure of 6.8×10^{17} protons was 2×10^{15} neutrinos.

If a reasonable theoretical model for monopole production by neutrinos were available the cross section form could be substituted into eq. (1) to yield a value for a monopole-neutrino coupling constant. To our knowledge no satisfactory model exists for this process. Therefore, we have followed our earlier practice [7] in evaluating the cosmic ray neutrino monopole production limit by assuming the cross section was a constant above a threshold energy E_T. Effectively this integrates the neutrino spectrum above E_T so that it is equivalent to counting the number of neutrinos above E_T.

A 95% confidence level on the upper limit for monopole production can be established by setting $N_M = \ln 20$ (essentially 3 events). For every value of E_T there will be an associated cross section limit $\sigma(E_T)$. This cross-section limit per nucleus is plotted in fig. 5 for scan criterion (i), that is the one-tenth of the film rescanned looking for tracks leaving the chamber along magnetic field lines. For this situation $N_p = 6.8 \times 10^{16}$ protons.

The cross-section limits have been calculated per nucleus rather than per nucleon. This facilitates comparison to our reevaluation of a cosmic ray monopole search to establish an upper limit on monopole production by neutrinos. The rationale is that neutrino monopole production would perhaps be a coherent process.

Searches (ii) and (iii) for "vertices" cover cases where the production mechanism for magnetic monopoles might be such that nuclear excitation or elementary particle formation occurred. No candidates were found. In addition, no candidates were found for search, (iv), the search for cases with diffusion times greater than the sensitive time of the chamber. For these cases all of the film was searched so that the neutrino exposure is calculated for 6.8×10^{17} protons incident on the production target for the neutrino beam. In effect this lowers the cross-section limit for these cases, that is production with target vertex excitation or long diffusion times, by 10. Thus for scan criteria (ii), (iii), and (iv) cross-section limits 10 times lower

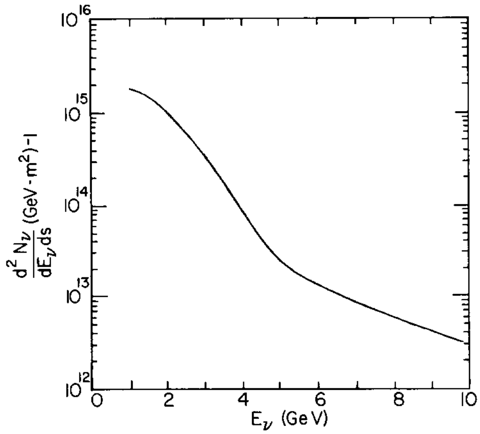

Fig. 4. Neutrino spectrum for the propane exposure (6.8×10^{17} protons).

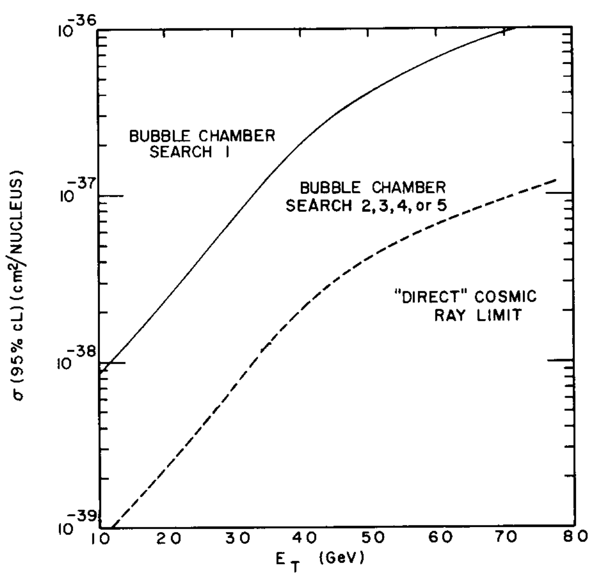

Fig. 5. 95% cross-section limit per nucleus for the CERN 1967 propane neutrino exposure. The solid line is based on the search (1) criterion. The dashed line is the limits for search criteria (2), (3), (4), or (5). For comparison the cosmic-ray limit for direct neutrino production has also been plotted as a dotted line.

than scan criterion (i) hold. This cross-section limit is plotted in fig. 5 as a dashed line. A similar argument holds in search (v) for showers resembling Ruderman-Zwanziger events. Again no events were found in the entire exposure.

4. Conclusions and comments

The limits established by this experiment roughly correspond to limits for free pole production that we have determined from reexamining previous cosmic ray monopole searches in which poles were assumed to arise from direct neutrino production in the sample that had been searched. For comparison the cosmic-ray limit on "direct" neutrino production of magnetic monopoles has been plotted in fig. 5. The bubble-chamber limits are larger by a factor of 10^5 than the cosmic-ray limit established by assuming that monopoles were collected from their surroundings. In our reexamination of the cosmic-ray searches we have suggested that the direct production limits represent more conservative estimates because they involve less consideration of binding effects. Even stronger arguments apply to these bubble-chamber limits since no hypothesis needs to be made concerning the way in which the poles arrive in the chamber or how they are bound in a collector.

None of our bubble-chamber searches place very strong limits on the hypothesis of the existence of neutrino produced magnetic monopoles since the neutrino energy available in the bubble chamber ($E_\nu \leqslant 10$ GeV) can only produce modest monopole masses. Even assuming coherent production, masses of greater than several GeV would not have been produced. However, the following should be noted. This search as well as the "direct" production cosmic-ray limit is near the reach of accelerator neutrino monopole production search techniques, while the "collection" limits for cosmic rays are beyond the present experimental capabilities. Substantial improvements on these limits at either existing accelerators or in cosmic-ray searches will require either new techniques or a considerable expenditure of effort. Bubble chamber neutrino film taken on hydrogen is now available at Fermilab. If monopoles are found, analysis on hydrogen film will be quite straightforward. However, for searches for free and bound poles the 1967 CERN film is unique because it was taken with an unusually suitable field configuration for monopole searches and cosmic-ray rejection and had a short radiation length.

We have examined the possibility of installing large tanks of liquid in the neutrino beam at Fermilab with foil collectors inside for monopole trapping. Even with an optimistic neutrino exposure and tank lengths of tens of meters it is only barely possible to approach the cross-section limit for cosmic ray neutrino production that we have published earlier using the "collector" hypothesis. Thus at present the most stringent limits on the possibility of magnetic monopole production by neutrinos are determined by examining the deep sea "collection" limits for magnetic monopoles. This situation may well hold for some time.

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